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Improving the Accuracy of the Active Power Load Sharing in Paralleled Generators in the Presence of Drive Motors Shaft Speed Instability

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***Abstract*—The paper suggests an improved method of active power distribution among the gas-diesel generators operating in parallel; the method involves the control of torque and the angular positions of their rotors. The use of the suggested approach to the solution of the active power distribution task in the presence of instability of drive motor speed provides the increase of autonomous power system operation efficacy and rising the power unit's performance. The authors analyzed the causes of generation of low-frequency fluctuations of generator drive engine speed; in autonomous electric power systems, gas diesel generators are increasingly used as such generator drive engines. It is suggested to use the developed method and structure of the optical device for control of rotation period and the measurement of the generator rotor angle position characterized with high accuracy, as the sensor. The authors developed a schematic diagram of active power distribution among the generators operating in parallel, which uses the cross feedback for gas-powered diesel engine shafts momentum and the generator rotor angle position. They obtained experimental results confirming the efficiency of the suggested active power distribution method and its practical implementation.**

***Keywords*—active load sharing, frequency instability, gas-powered diesel engine, optical sensor, rotor angular position**

I. Introduction

ONE of the most important parameters of diesel autonomous power plants is the cost-effectiveness, which is determined by the ratio of the power generated to the fuel consumption per an operation hour. The fuel consumption reduction will provide the improvement of power efficiency of autonomous power systems (APS). The optimal diesel-generator load is the load proximal to 80% of their rated power [1]. When a diesel-generator operates at lower loading, the specific fuel consumption increases with the development of carbonization effect caused by accumulation of incomplete combustion products, which produces a negative effect on the engine resource. The generator unit loading above 80% also results in significant performance reduction [1, 2].

The increase in the diesel fuel price results in the need to convert diesel vehicles to gas. Currently, gas-powered diesel-generator sets (GDGS) are widely used to provide reliable power supplies at industrial facilities. Gas-powered diesel-generator sets (GDGS) are increasingly used due to their cost effectiveness. Compared with a diesel power plant, gas-diesel plant provides lower fuel costs, long-term continuous operation with a standard fuel tank, the possibility of efficient use of gas of various chemical composition [3]. Despite the significant advantages of a gas-powered diesel engine over the diesels operating on liquid fuel, in particular, lower electric power cost, the quality of electric power often does not meet the specified requirements due to the fact that gas diesels are characterized by significant fluctuations in speed [4, 5]. The existing shaft speed fluctuations are due to the significant nonlinearity of gas diesel dynamic model and the change of its parameters with the change of the load. Fluctuations in generator drive motor shaft rotation speed causing the fluctuation of the generated voltage frequency, are the key factors in parallel operation of machines, because they cause the exchange power fluctuations, which can reach unacceptable values and result in electric power systems collapse. Exchange active power fluctuations can be especially expressed if gas-diesel engines are used as the generator drive motors. As indicated in [6], the uneven distribution of active power between gas-diesel generators during their parallel operation for total load can reach 50% of the rated power. Therefore, for both industrial and autonomous electric power systems, there are strict standards for generating voltage frequency fluctuations.

The literature analysis shows that there are several causes resulting in low-frequency fluctuations of diesel engine revolutions. The results of the research in [7] indicates the probability of speed fluctuation and degradation of diesel dynamic properties die to the discrete nature of retrieval the information about diesel shaft revolutions. It is established that if the information retrieval discreetness is close to or lower than the interval between the two flashes, run-outs may occur in the cylinders resulting in speed irregularities. Paper [8] indicates, that one of the causes of self-induced fluctuations in the closed automatic control systems of internal combustion engines is the presence of dead zones in fuel supply deices. In the considered engine structure such zone ε/2 takes place in pulse-width regulator of air (gas) supply valve which results in reduction of the contour amplification ratio.

The main cause of such detectible speed fluctuations is the fuel supply irregularity, because the gas is supplied without any pre-treatment and, possibly, the inconsistent calorific value of the gas. Similar conclusions were made in [9]. In [10], the authors

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point out another cause of the diesel torque and speed fluctuations – the irregularity of the fuel injection advance angle, which actually confirms the results of [8]. The performed analysis shows that the existing range of destabilizing factors of the engine operation does not allow predicting the fluctuations in its shaft speed, and, even more, determination of their numerical values.

It is very important to control the angular positions of the rotors of synchronous generators when they work in parallel for active power distribution, synchronizing the unit operation, in case of sudden load changes, or using GDGS of different power and type. This is due to the fact that with the generation of shock torque and abrupt changes in the rotor speed, the phase shift rise occurs in the GDGS control system. In this case, the total phase shift between the speed deviation and the torque on the shaft (active power distribution system input-output) exceeds the permissible phase stability margin, and the GDGS goes into the self-oscillation mode.

It is a well-known phenomenon described in [11, 12], which consists in the fact that with relative rotor oscillations in antiphase, there occur fluctuations of the unit rotor revolution angles relative to the synchronous speed. Therefore, the mechanical torque of a diesel engine, like the electromagnetic torque of a synchronous generator, is represented in the form of two components of the rotor revolution angle relative to the synchronous speed and synchronizing speed, proportional to the angle deviation.

Stabilization of the frequency and voltage of the autonomous power plant grid plays an important role in providing the efficient operation of electric power consumers. The task of search for new methods and effective technical solutions to reduce active power fluctuations between gas-diesel generator units remains important.

II. The Objective of the Research

The aim of the research is to improve the process of active power distribution between gas-powered diesel-generator sets operating in parallel for total load and characterized by shaft speed instability, by means of introducing of cross-feedback for torque and angular positions of the power units' rotors into the control system, using optical control of electrical machine rotor rotation periods.

To reach the set objective, the following tasks should be solved:

1. To analyze the causes of low-frequency fluctuations of gas-powered diesel-generator speed that precondition the active power fluctuation in the power system at parallel operation of gas-powered diesel-generators for total load and consider the options of reduction of such fluctuations.
2. To develop a method for generator rotor rotation period control and determination of its angular position that would possess the high accuracy of the specified parameters measurement compared to the existing Hall-effect optical sensors and suggest its technical implementation.
3. To develop a schematic diagram of active power distribution among the generators operating in parallel for total load, to determine the composition of sensors and relation between individual system elements for its implementation on the basis of microprocessor technology.
4. To perform experimental tests of the system in which the improved method of active power distribution between the generators is implemented, and assess its efficiency.

III. Development of a Method and Technical Means for Active Load Sharing

A- Analysis of the cause's gas-powered diesel-generator speed instability:

For perfect GDGS control system, in which there are no lags and pure delay, and the control is based only on the speed deviation, the mechanical momentum is purely damper, proportional to the angle derivative. If the system features with time lag and phase shift, in the mechanical momentum there occurs the synchronizing component which causes the change of the momentum sign, that is, passing the zero position in half of the fluctuation period. Here, the damper momentum begins swinging, and the system reaches the stability limit.

Therefore, to solve the task of excluding possible self-fluctuations and improve the system stability, first of all, it is necessary to find a method for increasing the stability margin taking into consideration both the constant delay Zd, and the phase shift Ψp.

It is known [11], that the electromagnetic power of the generator P, operating in parallel with others, is the function of EMF EQ1 and EQ2 of the both generators, grid frequency of the both generators, grid frequency fn, the angle between the rotors δ12, and load resistance ZL:

$$P = f\left(f_n, E_{Q1}, E_{Q2}, \delta_{12}, Z_L\right) \tag{1}$$

Let us linearize the equation (1) for the considered task of active power distribution, assuming that the generators loads and excitations are unchangeable:

$$\Delta P = \frac{\partial P}{\partial f_n}\Delta f_n + \frac{\partial P}{\partial \delta_{12}}\Delta\delta_{12} + \frac{\partial P}{\partial\left(P\delta_{12}\right)}\Delta\left(P\delta_{12}\right) \tag{2}$$

where the first component considers the change in electromagnetic power, the second – the change in electromagnetic power depending on the misalignment angle between the rotors. This power is synchronized; it is stipulated by irregularity of its distribution between the generators. The third component considers the synchronous power and is created by the transversal circuits of the generators operating in parallel [12].

Therefore, in the general case, the following task solution ways can be identified according to the torque (mechanical, electromagnetic and inertial) affecting the shaft:

1. increasing stability by increasing the flyweight (inertial moment). This way is unacceptable due to design features;
2. supplementary effect on the generator electromagnetic moment by changing the excitation regulator parameters. This method can degrade the power quality characteristics;
3. improvement of automatic load distribution devices. They are focused on the control of prime engines, based on the proportions between the active components of the generating sets currents;

4. additional regulation of the prime engines (diesels) based on the derivative of the difference in active loads of operating generators, the equivalent derivative of their rotors misalignment angle, as well as the derivative of GDGS rotation frequency deviation.

Let's take an example of improving the stability of parallel operation of two GDGS. The main indicators of parallel operation sustainability are:
damping coefficient of GDGS rotor oscillations:

$$\alpha = \frac{M_\text{D}}{2T_J} \tag{3}$$

natural frequency:

$$\omega_0 = \frac{\sqrt{M_S}}{T_J},$$

free oscillations frequency:

$$\omega = \sqrt{\omega_0^2 - \alpha^2},$$

where MD, MS are the specific damper and synchronizing torque created on the rotor by the rotation speed control system; T_J is the inertial constant GDGS.

Calculation of GDGS modes stability margins is based on the well-known provision of automatic control theory [13] – at free damping oscillations of the output parameter Δy of the system with W(p) a transfer function under the effect of input parameter Δx, the output parameter can be represented as:

$$\Delta y = \left\{ \mathrm{Re}\left[W(-\alpha + J\omega)\right] + \frac{\alpha}{\omega} y_m \left[W(-\alpha + J\omega)\right] \right\} \Delta x$$

$$+ y_m \left[W(-\alpha + J\omega) \frac{1}{\omega} \frac{d(\Delta x)}{dt} \right].$$

For mechanical diesel torque (DT) at rotor oscillation:

$$\Delta M = M(p)\Delta\delta,$$

where M(p) is the diesel speed transfer function:

$$\Delta M = M_S \Delta\delta + M_\text{DT}\left[\frac{d(\Delta\delta)}{dt}\right],$$

where

$$M_S = \mathrm{Re}\left[M(-\alpha + J\omega)\right] + \frac{\alpha}{\omega} y_m \left[M(-\alpha + J\omega)\right],$$

$$M_\text{D} = y_m \left[M(-\alpha + J\omega)\right] \frac{1}{\omega}.$$

A significant effect on stability is produced by the non-linarites, in particular, constant delay, which can be considered by the extra link:

$$W_\text{CD}(p) = e^{-\alpha\varepsilon}.$$

Link transfer oscillation ratio:

$$W_\text{CD}(-\alpha + J\omega) = e^{-\alpha\varepsilon}(\cos\omega\varepsilon - J\sin\omega\varepsilon).$$

Diesel self-leveling coefficient:

$$K_{SL} = -\left(\frac{\partial M_M}{\partial \omega_\text{G}}\right)\left(\frac{\omega}{M_{MN}}\right) \tag{4}$$

It is possible to consider by the supplementary damping torque:

$$M_\text{DT}^0 = K_{SL}$$

To assess the maximally possible contour amplification ratio and provide the set stability margin, we have elaborated the methods of GDGS modes stability calculation with supplementary control by the active loads derivative and GDGS rotations speed derivative.

The main system equations are determined on the basis of diesel dynamic model [14], and the parameters are selected based on the results of PID controller settings optimization [15]. They determine the control system transfer function in consideration of delay:

$$W_\text{CD}(P)M(P) = M(P)e^{-\varepsilon p}.$$

The quantitative transfer coefficient of the system is obtained from the expression (4) in accordance with equations (1), (2), (3) for stability limit condition $\alpha = 0$, $p = j\omega$, $\omega = 2\pi f_S$ (fS, is the natural frequency of DG self-oscillations).

According to the obtained quantitative coefficients, as per the formula (2) and (3), we obtain the expressions for calculating the dependences of the components of the specific damper and synchronizing torque values, as well as their total value depending on the constant delay value, where

$$M_\text{D} = M'_{\text{D}\max}\cos\omega\varepsilon + M''_{\text{D}\max}\sin\omega\varepsilon.$$

The electromagnetic, damper and synchronizing moments are determined through the transient parameters of the synchronous generator (x'_d, E'_q). The time constant TJ is determined from the known value of the inertial torque yDG of the GDGS flyweight. After that, the GDGS rotor damping coefficient α, the natural oscillation frequency ω0 and the free vibration frequency ω are determined. For the considered GDGS, the calculated frequency value is ω0 = 4 Hz. The calculations of stability indicators for parallel GDGS operation have shown that the frequency of free mutual oscillations does not differ significantly from the frequency ω0. It is due to the fact that under intense external disturbances, the parameters of which are studied in [16], the electromagnetic synchronizing torque provides the predominant effect on the unit's oscillation vibration frequency.

The optimization of GDGS regulators parameters during its single operation, performed in [15, 17], made it possible to actually increase the stability of the main engine speed to the conventional diesel unit speed stability. It provides the opportunity to insure their parallel operation, on condition of efficient control of the active power of each generator.

To provide the equality of the powers generated by each of the generators, it is necessary to provide the equality (proportionality at unequal installed powers) of the torque on the GDGS shafts and the equality of their rotations and rotor positions. Active power sensors can monitor both the actual active power component and directly the torque on the shaft. As we have mentioned above, the Hall-effect angular position sensors are characterized by the discreteness of the collection of information about the angular position of the generator rotor. Therefore, to improve the accuracy of monitoring the angular positions of the generator rotors, it is suggested to use the method and device for optical control of electrical machinery rotor rotation period developed by the authors.

B- The system of optical control of electrical machinery rotor angle positions

The device, implementing the method of optical control of electrical machinery rotor rotation period and angle positions is provided in Fig. 1, it contains electrical machine (synchronous generator) 1 with rotor 2, laser disk 3 with information sectors 4, laser reading system 5. The laser reading system is fixed on one side of the spring 6 on a round plate 7 with axial stem 8 and two consequently located bearings 9 attached in an immobile casing 10. On the other side of the spring, there is a flexible rubber round plate 11 with high friction coefficient, contacting with the electrical machine rotor butt end.

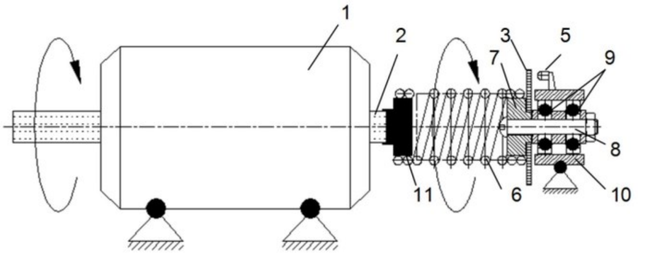

Fig. 1. The structure of the system for measurement of rotation period and the angle position of the electrical machine rotor

The device implements the process of rotation period optical control and determination of the generator rotor angle position as follows. The spring, functionally linked with the laser disk by means of flexible rubber round plate directly contacts the electrical machine rotor butt end, therefore, the laser disk with informational sectors traces the rotor rotations. Subsequently, the laser disk informational sectors from the electrical machine start definitely correspond to the electrical machine rotation period Tω, and the laser reading system generates electrical pulses which may perform high-accuracy control of electrical machine rotor revolution period. It should be noted that the use of the spring in this device makes it possible to exclude the transfer of the electric machine rotor oscillating motion of the laser disk.

The process of generation of information arguments containing information about the period of rotation (Tω) of the rotor «ωRotor» of the three-phase generator f1-3(TorGener±Uφ1-3) and, accordingly, the drive gas-diesel unit f1(DrivePowerω±Δω), is described by the graphic-analytical expression presented in Fig. 2. The process of generation of the «Information sector (Tωt)» to activate optical information arguments (ΔhνjInformTω) of the rotation period «ωRotor» of the rotor «RotorGenerDrive» is performed using the disk f1 (InformDiskTω), at which the continuous optical radiation (hν) formed by the LED f1(n-p↑hν) is directed. The optical radiation, reflected from the disk, is of discrete nature of information arguments (ΔhνjInformTω) and is received by a semiconductor structure – photodiode f1(↓hνn-p). Next, voltage informational arguments [hνΔUInformTω] are formed, which are fed to the first input port f1(↓Port) of the microcontroller f1(CoreMK). The reference voltage [ΔUjTω]ref is fed to the second input port f2(↓Port) of the microcontroller to form a correction signal [ΔUi±ΔTω±Δω] at the port output f1(Port↑). This signal controls the stepper motor (or DC motor) f1(DriveStepTω) to change the position of the gas-diesel generator fuel rack, and, accordingly, the torque on the shaft (MomRotorTω±Δω) of the drive motor – gas-diesel unit f1(DrivePowerTω±Δω).

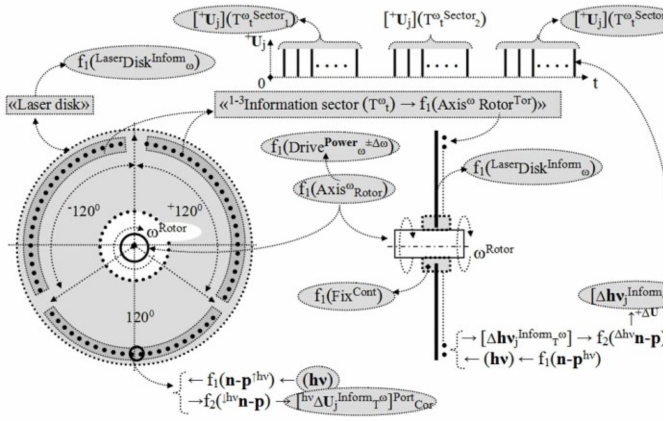

Fig. 2. Graphical analytical model of the process of measurement of rotation period and the angle position of the generator

In this case it is supposed to use the laser disk f1(LaserDiskInformω) as the functional structure of the disk f1(InformDiskTω), on the surface of which the optical information [hνΔUjInformTω] → [ΔUjTω]ref is recorded in one «1Information sector (Tωt)» or some subsequent «1-3Information sectors (Tωt)» [+Uj](TωtSector1), [+Uj](TωtSector2) and [+Uj](TωtSector3); the information corresponds to the informational arguments of voltage of the reference period «Tωt» of the rotor «RotorGenerDrive» rotation. Recording of optical informational arguments of the reference period Tref in subsequent «1-3Information sectors (Tωt)» [+Uj](TωtSector1), [+Uj](TωtSector2) and [+Uj](TωtSector3) on the laser disk f1(LaserDiskωInform±Tωφ1-3) surface in performed inside the «1200», and on its edge the optical informational arguments corresponding to the information about the phase φ1, φ2 and φ3 in three-phase generator f1-3(TorGener±Uφ1-3) are recorded. The process of measurement of the period and the generator rotor angle position, microcontroller processing and generation of a control signal to the control motor of gas-diesel unit fuel valve is presented in Fig. 3.

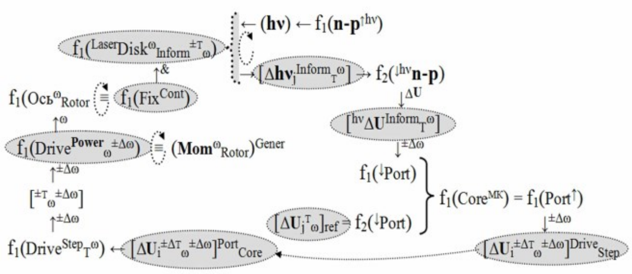

Fig. 3. Graphical analytical model of the process of gas-diesel unit rotations control

By means of the the contact structure of the f1(FixCont) retainer, the laser disk f1 f1(LaserDiskωInform±Tω) is fixed on the rotor axis f1(AxisωRotor) of the drive f1(DrivePowerω±Δω) or the generator f1-3(TorGener±Uφ1-3) for joint rotation. In this case, the functional semiconductor structure f1(n-p↑hv) of optical radiation (↑hv) (LED) and the functional semiconductor structure f1(↓hvn-p) for receiving optical radiation (photodiode), at the output of which the structure of informational arguments [ΔhvjInformTω] is formed, are located on one side of the laser disk f1(LaserDiskInformω) opposite one of «1-3Information sectors (Tωt)» to activate the structure of voltage informational arguments [hvΔUInformTω].

C- Development of the active power distribution system structure

The general schematic diagram of the system of active power distribution between GDGS operating in parallel, using the feedbacks on the diesel engine shafts torque and the angular positions of the generator rotors, is presented in Fig. 4.

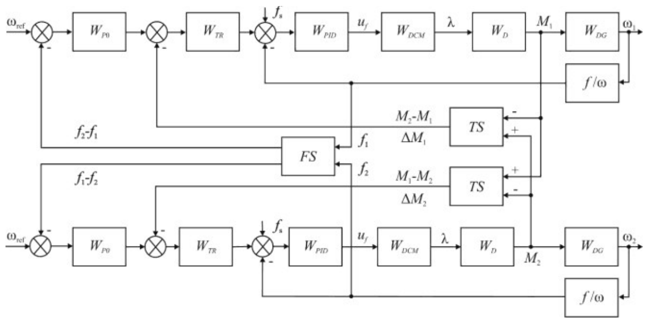

Fig. 4. Schematic diagram of active power distribution system

The figure uses the following symbols: ωref – frequency reference, WP0 – speed regulator transfer function, WTR – torque regulator transfer function, WPID – PID-regulator transfer function, WDCM – DC machine transfer function, WD – diesel transfer function, WDG – diesel-generator transfer function, f/ω – angular to linear frequency conversion unit, fs – external disturbances affecting the speed of the diesel generator shaft, uf – DC machine control voltage, λ – fuel rail position, TS – torque sensor, FS – frequency sensor.

The rotations control is performed according to the operation principle of generator frequency automatic phase lock systems used in radio transmitting devices. When the frequency equality is provided, the circuit of rotor position control of the both generators actuates. The system can be built both on the basis of interrelation of generators according to the driving-driven principle, and on the cross-relations basis as per the Fig. 4. Next, the frequency difference is determined (Δf12=f1–f2, Δf21=f2–f1 variables). If the frequencies are equal (or almost equal), then, the values Δf12 and Δf21 are equal (by module) within some period of time. When such mode starts, the control system microcontroller shifts from the frequency sensor (FS) mode to phase detector mode and performs the phase equalization function.

To implement to above-suggested method of active power distribution between the generators operating in parallel, the authors suggest a structural diagram of microprocessor active power distribution system, presented in Fig. 5.

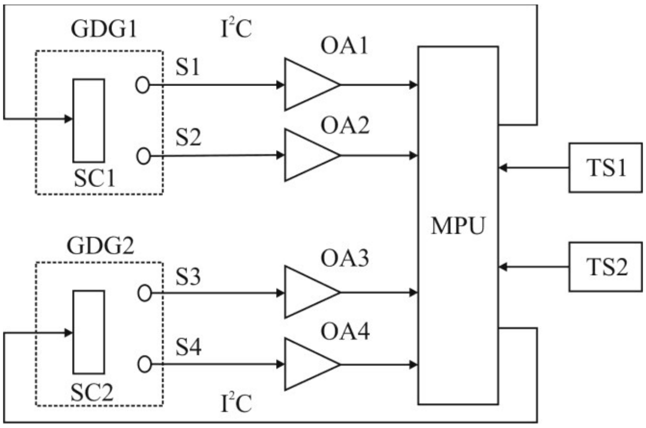

Fig. 5. Structural diagram of microprocessor active power distribution system

Its operating principle is as follows. Two induction sensors S1, S2 and S3, S4, respectively are located on the flywheel of both gas-diesel generators (GDG1 and GDG2). The pulse signal from the output of each of these sensors is fed to the operational amplifiers OA1-OA4, where it is amplified to the required level and fed to the MPU microcontroller. Therefore, the microcontroller has complete information about the position and rotational speed of rotors of the two generators as well as the information about the value of the torque on the shafts of both diesel engines from the torque sensors TS1 and TS2 or the active power sensors obtained at the output of synchronous generators. In case of significant nonlinearity of the load, for example, if there are semiconductor converters of comparable power, the isolation of the active power component of in the AC network becomes troublesome, therefore, obtaining the information about the value of the moment on the shaft is possible either using the torque sensors that are installed on the shafts of diesel engines, or indirectly, by excess pressure of the turbocharger. According to this data, the microcontroller calculates the misalignment angle (phase shift) between the positions of GDG1 and GDG2 rotors, proportional to the output active power. Then MPU performs the operations of multiplication, integration, differentiation with the set coefficients and time constants, and generates a negative feedback control signal at the output. The feedback signal is fed from the MPU through I2C bus to the input of the speed controllers SC1 and SC2, which, in turn, increase or decrease the fuel supply so that to maximally accurately maintain the set frequency of the basic GDG1 and the set phase lagging angle of the rotor GDG2 with respect to GDG1.

IV. THE RESULTS OF EXPERIMENTAL CHECK OF THE SYSTEM OPERATION

Fig. 6, a, presents the curves of the change of the two GDGSs speeds when there is a feedback by the control generator rotors angle position and the torque on the diesel generators shafts. The Fig. 6, b, presents the similar dependencies at the absence of the GDGSs torque feedback.

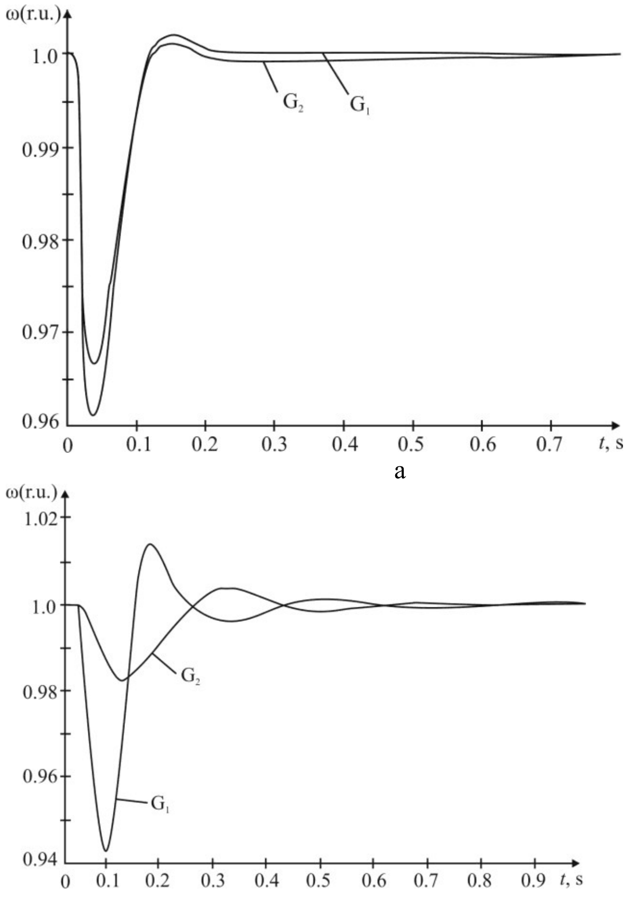

Fig. 6. The curves of the change of the two GDGS speeds: a – with the feedback; b – with no feedback

From the diagrams obtained it follows that the provision of control of GDGS rotors angle position and the torque on the shafts of each diesel generator provide the proportional power distribution both in static and in dynamic modes. The irregularity of the active power distribution does not exceed 2%. Therefore, the use of the active power distribution process suggested in the work, in complex with the method of the diesel generator units' structural composition optimization described by the authors in [18], in general, provide the improvement of efficacy of diesel- and gas-diesel autonomous power plants operation.

V. Conclusions

1. As a result of the analysis, it was found that in order to reach the energy efficiency of autonomous electric power systems and provide the high quality power generation, it is necessary to implement new automation hardware and software and the methods of control of individual power units. It is necessary to take into account their parallel operation for full load, since the uneven distribution of active power due to the presence of speed instability can reach 50% of the rated power. The key control principles should be the principles of continuity and process compatibility – the modernized automation tools must be combined with new technologies for autonomous power facilities control and designing the automated control systems.

2. The scientific novelty of the obtained results consists in the fact that the method of active power distribution between the generators operating in parallel was improved by monitoring the torque and angular positions of the power units' rotors, which is its distinctive feature. It is shown that the use of the proposed method makes it possible to reduce the uneven distribution of active power to a value that does not exceed 2% of the generator rated power.

3. To develop a schematic diagram of active power distribution among the generators operating in parallel for total load, to determine the composition of sensors and relation between individual system elements for its implementation on the basis of microprocessor technology. The use of microprocessor technology can reduce the cost of hardware and software automation by 10-15%.

4. The practical implementation of the improved method suggested in the work provides the improvement in the energy efficiency of the autonomous electric power systems due to reduction of the active power fluctuations between generators and providing such a control strategy in which the power units operation takes place in the modes characterized by the highest performance. The use of the proposed method and technical means of active load sharing in conjunction with the method developed by the authors to optimize the composition of diesel generator sets in autonomous power plants, allows to reduce fuel consumption by 3-5%.

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